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Pathogenesis of Cervical Spondylotic Myelopathy

- Experimental and clinical Studies -

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Introduction

Figure I shows a histological picture of the cord in an advanced case of cervical spondylotic myelopathy. It is considered that the pathogenesis of this condition may be concealed in this selective cord lesion of the central area and the lateral columns. It is difficult to explain this cord lesion solely on the basis of cord compression. Therefore, the various pathogenetic factors and theories have been reported[1,2,4,6,7,8,9,10,11,12,13,16,18,19,20,22].

Typical theories are as follows :

As for the vascular theories ; MAIR and DRUCKMANN[8] (1953) have attached a causal significance to the anterior spinal artery from the histological findings of the transverse cord in the postmortem examination. It is however denied that the ischemia of this artery may produce the lesion in the lateral columns seen characterisitically in this condition, for the branches of this artery scarcely supplies the lateral columns according to the recent research of intramedullar vascular system.

FUKUDA[22] (1968) has suggested that such cord lesion as seen in this condition may be produced by obstruction of the perimedullary arteries including the anterior spinal artery, the posterior spinal artery and the pial arterial plexus. It is, however, probably impossible to explain that all these arteries may be obstructed around the cord and the same lesion as that in this condition may be produced, for obstruction of all these arteries would damage equally the transverse cord.

BREIG[3] (1966) has emphasized that the ischemic change in the lateral columns may be produced by narrowing of the blood vessels following elongation of the cord by compression because of these blood vessels running cross to the direction of force, while the ischemic changes in the posterior column and the anterior column may not be produced be widening

Key Words : intramedullar stress distribution Selective, experimental cord lesions. types of spondylotic myelopathies. dynamic and static cord compression. measurement of the spinal canal. shapes of the spinal canals. myelographic defects.

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Fig. 1. A Histological Picture in Cross-Section of the Cord in Cervical Spondylotic Myelopathy (BRAIN et al. 1952)

Table 1. Mysterious, Selective Cord Lesion

Theoretical, Mechanical	Theoretical, Ischemic
· Anchoring Effect of the Dentate Lig. (KAHN 1947)	· Ischemic Border Area between Anterior and Posterior Spinal Artery (TÖNNIS 1961)
· Mobility of the Spine (REID 1960)	· Anterior Spinal Artery (MAIR and DRUCCKMANN 1953)
· Pincers Mechanism (PENNING 1966)	

Experimental

· Intramedullary Microvascular Ischemia due to the Stresses (BREIG et al. 1967)

of blood vessels following constriction of the cord because of these vessels running parallel to the direction of force. It is, however, impossible to explain by this theory that the ischemic changes in the central area of the cord are seen characteristically in this condition.

TÜNNIS[17] (1961) has suggested that the area between the anterior spinal arterial system and the posterior arterial system may be particularly vulnerable to damage by cord compression, and also ZÜLCH (1954) feels that the area consisting of the inner one quater of the while matter and the outer edge of the grey matter supplied both by the central artery and pial arterial plexus may be particularly changeable when there is a general reduction of blood flow.

As for the mechanical theories, on the other hand ; KAHN[7] (1947) showed diagrammatically the lines of the stresses concentrating on the lateral columns produced by the tethering action of the dentate ligaments in cord compression, while PANTEK[16] (1956) measured and plotted the magnitude of the stresses acting on each part of the cord from deformity of the grid drawn on the cervical cord models of cross-section made of foam rubber. These results seem, however, to be lacking in an actual proof, for their studies are very theoretical or undertaken without carefull consideration of the dynamical nature of the cervical cord.

The study on the effects of the stresses to the blood vessels within the cord was first undertaken by BREIG[2] (1966) who examined ischemic condition in cord compression by means of microangiographic procedure. Consequently, ischemic condition in the lateral columns has been proven but that in the central area of the cord not proven, for the relationship between the deformity of the cord and the pathways of the blood vessels in the cord would not be examining as precisely as in living condition since their study was made by using the cervical cord specimen with a dynamical characters changed remarkably by fixation.

Thus, these theories above mentioned are very theoretical and have made up without carefull cosideration of the dynamic nature of the living human cord.

The problems ; How would any stress produced in cord compression precipitate any of blood vessels into ischemia ? How would this selective cord lesion be caused ? To solve these problems would be a clue to solve this mysterious pathogenesis.

Part I. Mechanical Experimental Studies

1. Dynamical Characters of the Cord

a. Intensity of the fresh bovine cord in cross-section

The dynamical intensity of cross-section of the lower cervical cord of the fresh bovine which was picked up immediately after slaughter was measured by the dynamical instrument. Consequently, it became apparent that cross-section of the cervical cord is weaker several times to the tensile forces than to the compressive forces, and also the grey matter of the cord is softer, more fragile than the white matter.

b. Observation of deformity of the cord in comression

The state of the deformity of the cord of when compressed by a median load from forward and supported by a curved board like the laminal arch from backward was observed. In a slight load, the cord became easily flattened, deformed like a butterfly and lenghtened

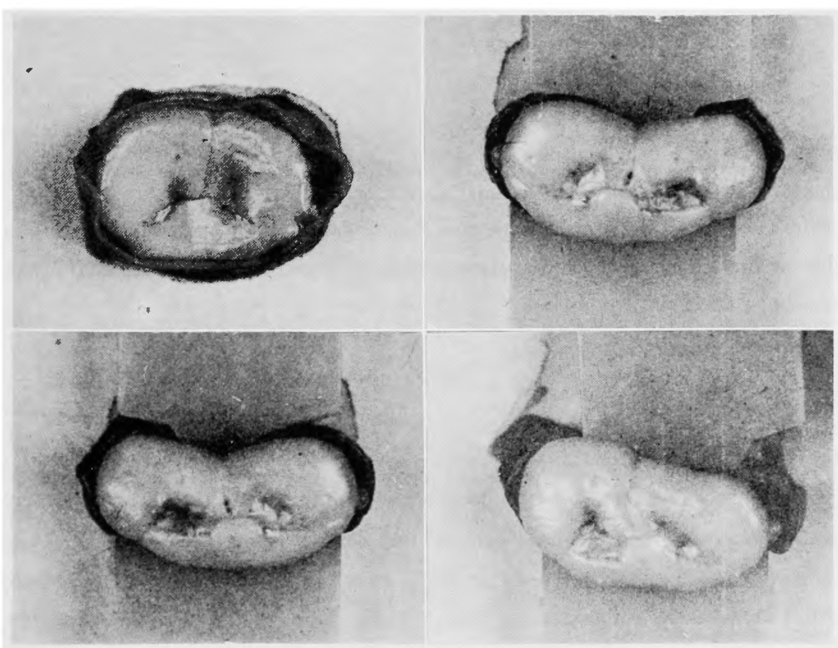


Fig. 2. Deformity of Fresh Bovine Cervical Cord in Various Degrees of Compression

to a lateral direction to the maximun in the central area, and also became more tense in the outer edges of the posteolateral areas. In a severe load, the cord became remarkably deformed especially in the grey matter and more tense in the outer edge of the lateral areas, and at last was destroyed in this area. Consequently, it became apparent that the cord in compression is severely damaged especially in the central area and the outer edge of the posterolateral areas.

2. Photo-elastic Experiments

a. Two-dimenisonal photo-elastic experimental models

Imitating the form of human cervical cord, the photo-elastic cord models were made of polyurethane rubber, which were excavated in the grey matter considering the difference of the elasticity between the grey matter and the white matter. This polyurethane was considerably soft and elastic, and its elastic modulus was 1.8kg/cm² and its elastic sensitivity was 12.5mm/kg. Furthermore, the dentate ligaments and dura matter were made of plastic rubber, a little harder than polyurethane rubber.

b. Photo-elasticity apparatus

The photo-elasticity apparatus was of The Japanese Physical Chemical Research Institute's make.

c. Method of Loading

As for the method of cord compression, the cord model was placed in this apparatus, then compressed by a iron ring with different degrees or weights from forward in a median or paramedian part, and supported by a curved board like the laminal arch from backward.

When the cord model is loaded and then illuminated by a mercury lamp, many beautiful striped patterns were observed through the lens of the apparatus. There is a formula between this striped pattern and the stress. Analyzing the striped pattern, the stress distribution could be maped out.

Table 2. Photo-Elastic Experimental Study

• Models	: made of polyurethane rubber
	• elastic modulus 1.8 kg/cm²
	• elastic sensitivity 12.5 mm/kg
• Methods	: Riken photo-elsatic apparatus
	: method of loading
	• median, paramedian compression
• Isochromatic Lines	
• Lines of Stress Distribution	
	• effect of the stresses to the spinal cord
	• effect of the dentate ligament to the spinal cord
• Dynamically Weak Area	
	experimental cord lesions

d. Isochromatic lines

The isochromatic lines set up by a slight median load first appeared in the central area and gradually concentrating on this area as the compressive stresses and the outer edges of the posterolateral areas as the tensile stresses. By a severe median load, the isochromatic lines of the tensile stresses spread from the outer areas of the posterolateral areas to that of the anterolateral areas, while those of the compressive stresses spread eccentrically from the central area to the outer area of the cord. By a paramedian load, many striped patterns occured even in the unloaded side. This shows that the effects of the stresses occured remarkably even in this side.

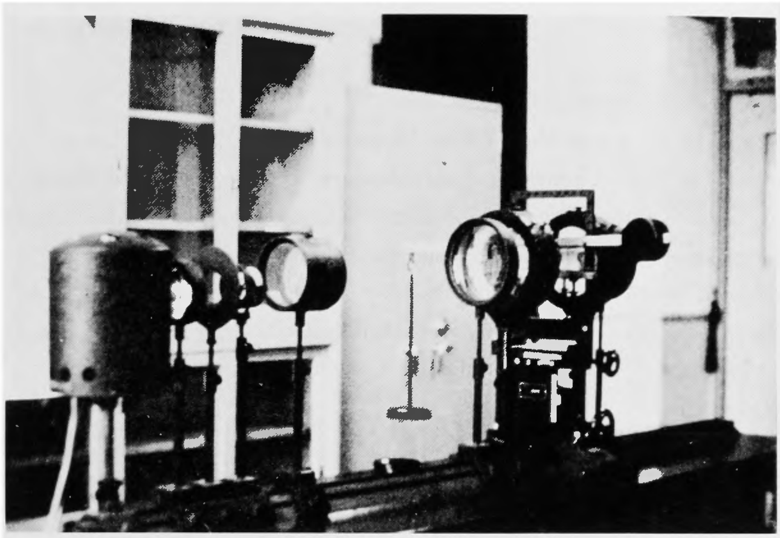


Fig. 3. RIKEN Photo-Elastic Apparatus

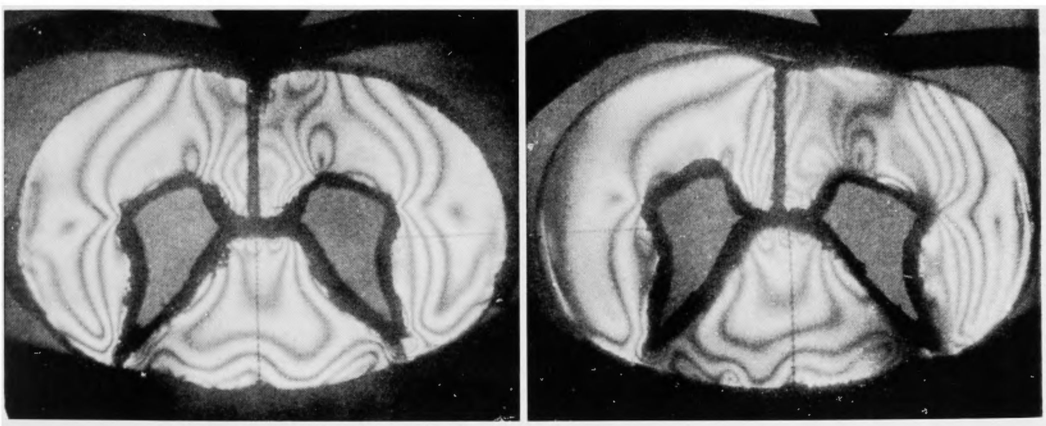


Fig. 4. Isochromatic Lines in Median and Paramedian Loading. The compressive stresses concentrate on the central area and simultaneously the tensile stresses on the outer edges of the posterolateral areas.

e. Lines of the stress distribution

From the isochromatic lines in each load of slight, moderate and severe load, the lines of the distribution of the principal stresses difference and the lines of the distribution of the edge stresses were diagramed. The diagrams explain that the compressive stresses increase to the maximum in the grey matter and decrease in the outer edge of the anterior area and the posterior area, while the tensile stresses increase to the maximum in the outer area of the posterolateral area and decrease in the outer area of the anterolateral area. Also, this shows that in slight compression the compressive stresses act on the central area, and simultaneously, the tensile stresses act on the posterolateral areas, and in severe compression, when the compressive stresses damage severely the central area, the tensile stresses move from the outer areas of the posterolateral areas to the outer edges of the anterolateral areas.

f. Effects of dentate ligaments to the cord

Furthermore, the effects of the dentate ligments to the lateral columns were observed. In slight compression, the dentate ligaments became slightly tense. In severe compression, however, they became rather flaccid. This may explain that the dentate ligments have not a tethering action enough to produce the lateral column signs.

g. Loading on longitudinal section models

In loading on the cord models in longitudinal section, the stresses increase especially in the central part and spread approximately to the two segmental levels.

3. Mechanical Loading Experiments

a. Cord models

Using the cord models made of plasster rubber with elastic modulus 1.8kg/cm^2, mechanical loading experiments were done.

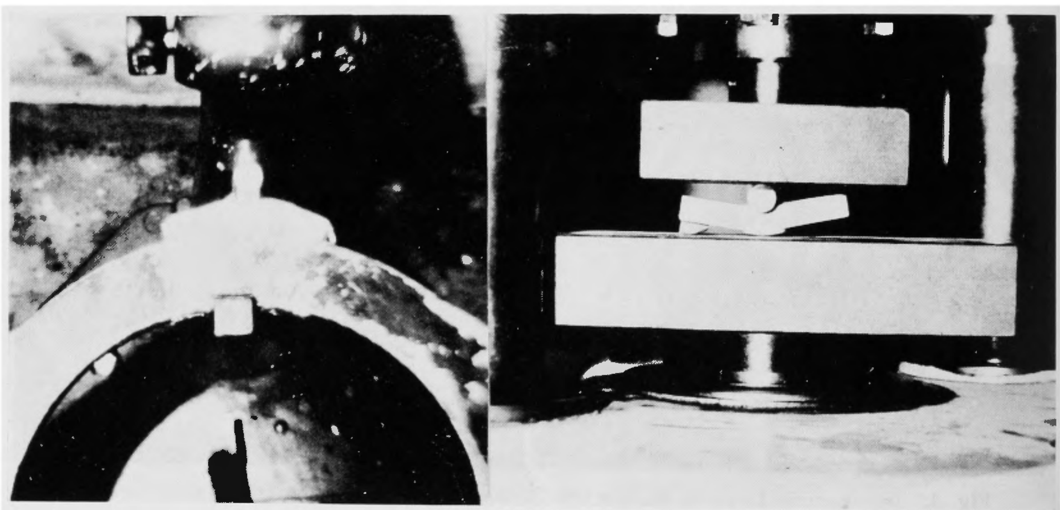


Fig. 5. Repeated, Dynamic Experiment Static Experiment

b. Comparison between static and dynamic loading

The intensity of the cord model was measured in the condition of the dynamic and the static compression by the dynamical instruments. Consequently, the cord model was more fragile to the dynamic, repeated slight loading than to the static severe loading.

Experimental Discussion

From these experimental results, it is apparent that dynamically weak areas are produced in the central area and in the outer areas of the lateral columns.

Recently, the blood supply of the cervical cord was demonstrated clearly even small vessels by microangiography[14][15]. The blood supply in the cord is consisted of both of the central and the peripheral arterial system.

Table 3. Mechanical Experiments

cord models	: plastic rubber
	: column shape 12mm × 20mm × 80mm
	: elastic modulus 1.8kg/cm^2
method 1	dynamic, repeated, impacted loading
2	static loading
1 - 30kg	: destroyed
2 - 30kg	elastic, not destroyed
50kg	: limit of elasticity
70kg	· destroyed

stress by dynamic load S = 2 S' stress by static load

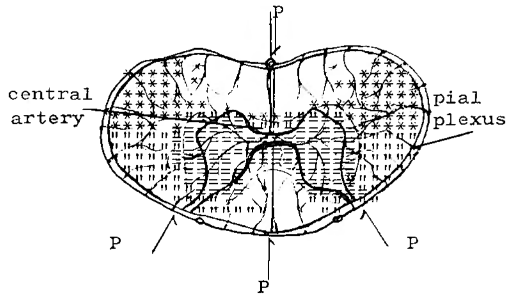


Fig. 7. Interaction between Intramedullary Stresses and Ischemia

The compressive stresses acting on the central area may disturb the central artery and its branches, while the tensile stresses acting on the outer edges of the lateral columns may disturb the lateral pial arterial plexus.

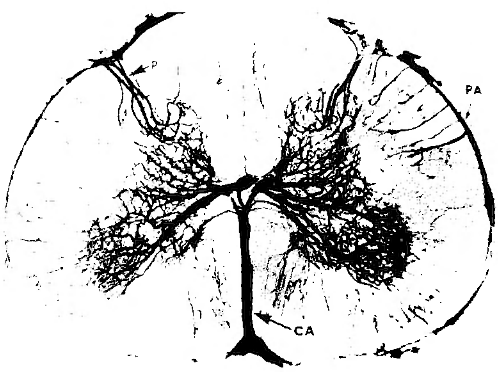


Fig. 6. Microangiogram of the cervical cord (Turnbull, 1966)

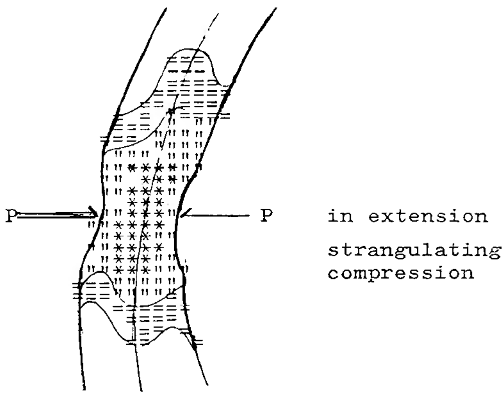
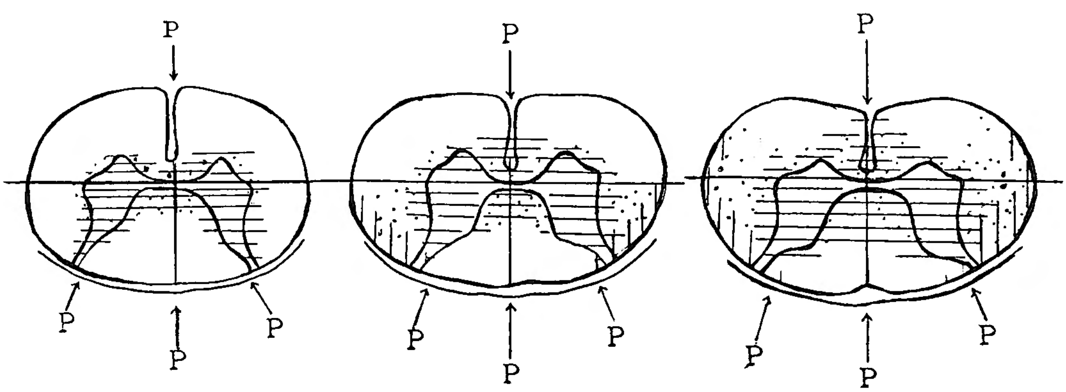


Fig. 8. Magnitude of stresses in longitudinal section of the cord



1. Central Lesion in Slight Compression
2. 1+Posterolateral Lesion in Moderate Compression
3. 2+Anterolateral (transverse) Lesion in Severe Compression

* Dotted area indicates that of ischemic changes.

Fig. 9. Cord lesions due to relation between the stresses and the pathways of the vessels in the cord

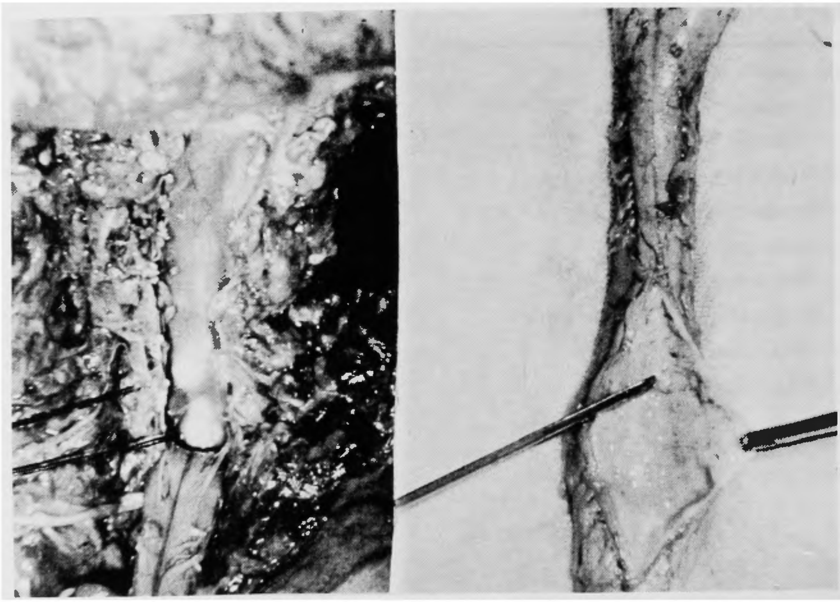


Fig. 10. Destruction of the Central Area in the Cord by Spondylotic Spur.

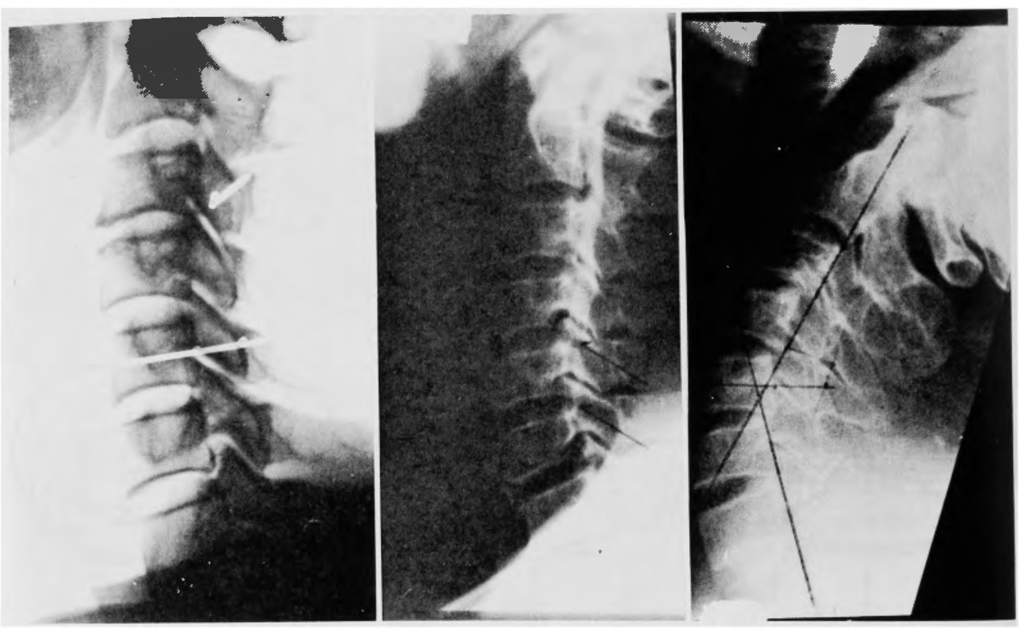


Fig. 11. Posterior Spur in Addition to the Narrow Canal

The Narrowed Canal by the Ossification of the Posterior Longitudinal Ligament

Dynamic Stenosis by Hypermobility of the Intervertebral Spases

Combining the pathways of the blood vessels with the stress distribution, it is presumed that the compressive stresses acting on the central area may disturb the central artery and its branches, while the tensile stresses acting on the outer edges of the lateral columns may disturb the lateral pial arterial plexus. Consequently, the central area and most of the lateral columns may be severely disturbed and damaged, while the anterior column and the outer area of the posterior column may be scarcely damaged even by severe compression.

The pattern of the cord lesion presumed experimentally is closely similar to the histological picture seen clinically.

The mechanical pathogenetic factors are as follows ; narrow canal, narrowed canal, ossification of the longitudinal posterior ligament, triangular-shaped canal, intervertebral hypermobility and retrolisthesis, and infolded ligamenta flava increasing in extension.

Experimental Conclusion

It is concluded that the pathogenesis of cervical spondylotic myelopathy has a basical and significant relationship to interaction between the stresses and the subsequent ischemia in the cord which are set up dynamically in cord compression, reinforcing by the repeated movements of the cervical spine with the narrowed canals.

Table 4.

* Material

Oparative cases: 100 (Robinson's interbody fusion)
non-oparative : 30 fusion)
Average period of follow-up 6 years 5 months

* Age

less than 30	6 cases	0	7	male	104
31 — 40	25	2	27	female	26
41 — 50	36	5	41		
51 — 60	29	13	42		
more than 61	7	10	10		
total	op. 100	non 30	130 cases		

* Duration of the Disease

less than		3 months	22 cases
4 m.	—	6 m.	31
7 m.	—	11m.	19
1 y.	—	2 years	21
more than		2 y.	35

Part II. Clinical Studies

Clinical Discussion

To discuss whether the hypothesis presumed experimentally could be accepted clinically, the following studies were done in connection with the mechanical factors of cervical spondylosis.

I. Material

The clinical material is 130 cases and 100 cases of them were operated with the modified Robinson's interbody fusion.

Age distribution reveals that this disorder is likely to be caused in imbalanced condition between activity in living and aging.

2. Pathogenetic Factors

a. Periodic factors

As for the periodic factors, the duration of the disorder is relatively long, however, most commonly the symptoms progress so rapidly when once the structural changes of the cervical spine become pathogenetic to the cord.

b. Structural factors

Among the structural factors, the basical, compressive factors are diagramed and each incidence is shown in Table 2. Spondylotic spur, discal protrusion and intervertebral retro-

Table 5.

Basic, compressive Factors

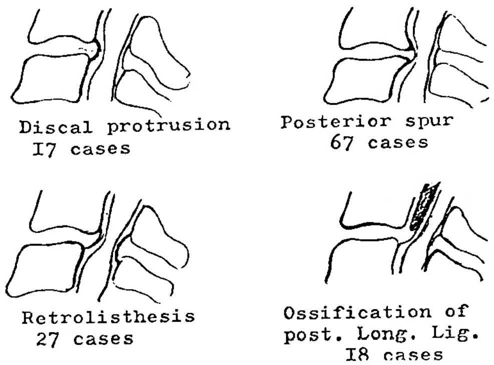


Table 6.

Neurological Cord Levels

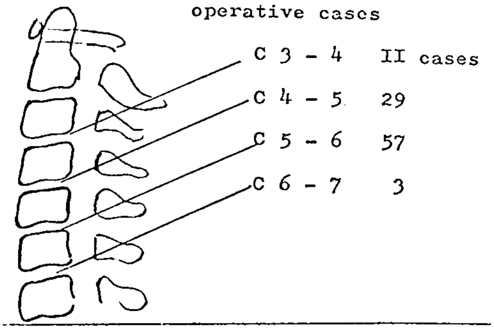


Table 7.

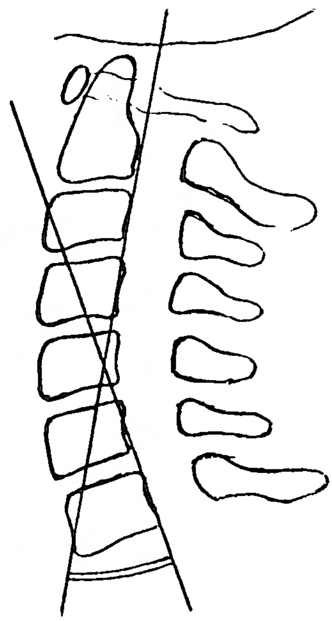
Mobility of the Cervical Spine

less than	20°	30 cases	49	20
21 —	30°	57	48	7
more than	31°	13	3	3
		preop.	post.	non.

Alignment

less than	10°	11 cases
11 —	20°	17
more than	21°	2

mobility = degree in extention
alignment = degree in neutral position



listhesis are conspicuous. Ossification ot the posterior longitudinal ligament is seen in 18 cases.

c. Mobility of the cervical spine

The neurological levels are almost included from C3 to C7 in this condition. Therefore, the cervical mobility among these levels are measured in the cross angle in stretching of the posterior marginal lines of C3 and C7 vertebral body in both extension and neural position. This angle in extention indicates the degree of the instability of the cervical spine, while the angle in neutral position indicates the alignment of cervical curvature. Consequently, the preoperative hypermobility of 30 degree or more has a close relation to the severity of the symptoms, while the postoperative hypomobility often leads to remarkable improvement of the symptoms.

d. Narrow spinal canal

The sagittal diameter of the canal was measured as the ratio of the width of the canal to that of the body in C5. The canal in this condition is apparently narrower than that in normal person. The narrow canal may be the basis of promoting cord compression. The ratio in normal person points out the peak in 1.00.

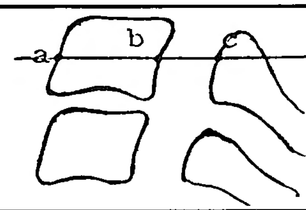
Table 8.

Narrowness of the Canal
Body to Canal Ratio in Sagittal Diameter in C 5

less than	0.60	29 cases
0.61 —	0.70	53
0.71 —	0.80	33
more than	0.81	14

* peak in normal person : 1.00

$\frac{bc}{ab} = R$

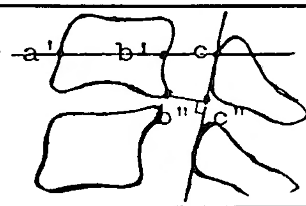


Narrowing of the Canal = Retrolisthesis
Body to Canal Narrowing Ratio

less than	0.51	32 cases
0.51 —	0.60	48
0.61 —	0.70	40
more than	0.71	10

* peak in normal person : 0.80
* intervertebral mobility

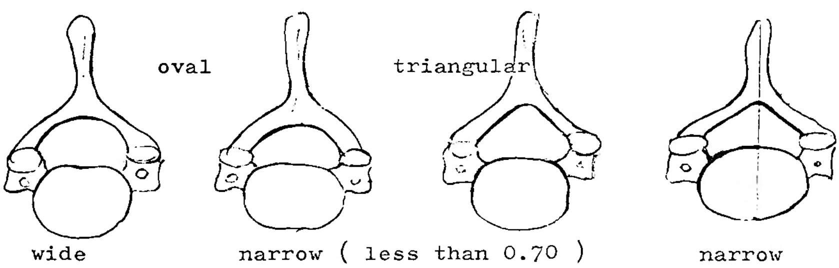
$\frac{b''c''}{a'b'} = R'$



e. Narrowed spinal canal

Also, the sagittal diameter of the canal narrowed by the intervertebral movement especially in extension was measured as the ratio of the width of the narrowed canal to that of the vertebral body in the pathological cord level.

This patient of Figure 13 was much limited in the mobility of the cervical spine postoperatively. His symptoms improved remarkably to be able to walk. After 7 years, the



Patterns of Laminal Shapes in Cross Section

oval, wide	5 cases
oval, narrow	8
Triangular, wide	4
triangular, narrow	35

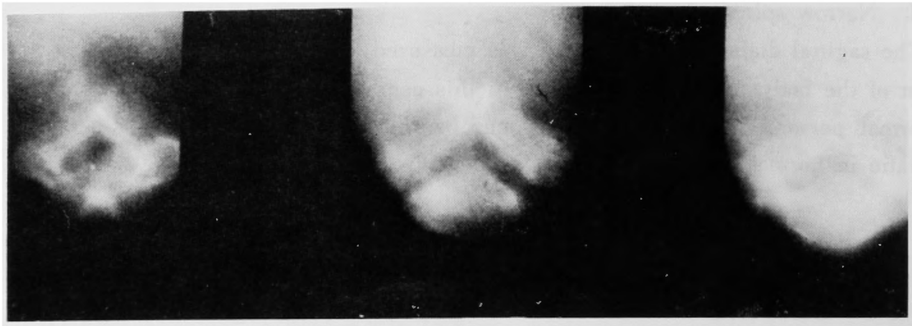


Fig. 12. Triangular -shaped Canal

intervertebral space of C3-4 became unstable, moreover, the canal corresponding to this level became so narrower that the cord was compressed again, and also the myelopathic symptoms reappeared.

f. Laminal shapes of the spinal canal in cross-section

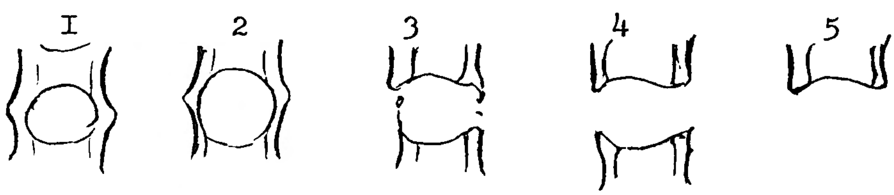
The shape of the canal in cross-section of C5 was clearly shown in a rotational tomogram. The pathological level was marked by the schmirator accurately. The triangular-shaped pattern with the narrow canal was recognized in 50 percent in this condition. Figure 9 shows a positional relation between the narrow canal and the posterior ossified mass[21].

g. Myelographic defects

It was then discussed whether the intensity of cord compression would have any relation to the degree of myelographic defects. Myelographic patterns were classified into five according to the degree of its defect, that is, central defect, lateral narrowing, lateral dropping, lateral defect and complete blockage. Complete blockage is seldom seen in the myelograms of this condition. In most cases, the contrast medium passed slowly in the flexed

Table 9. Patterns of Myelograms

proportional to grade of compression



central defect 15 cases	lateral narrowing 14	lateral dropping 36	lateral defect 37	complete block 7

position. This indicates that the mobility and the change of the position of the cervical position of the cervical spine delicately effect on the cord within the narrowed canal.

Figure 13 shows the dynamic canal stenosis in the levels of C3-4 and C4-5. The myelgram demonstrated lateral defect in these levels. The patient could walk steadily by himself by means of the interbody fusion of these levels.

3. Cord Factors

a. Classification of spondylotic myelopathy

The cord lesions presumed experimentally were classified into four types according to the areas of the cord damages. That is, cervical spondylotic myelopathy was neurologically classified into four types.

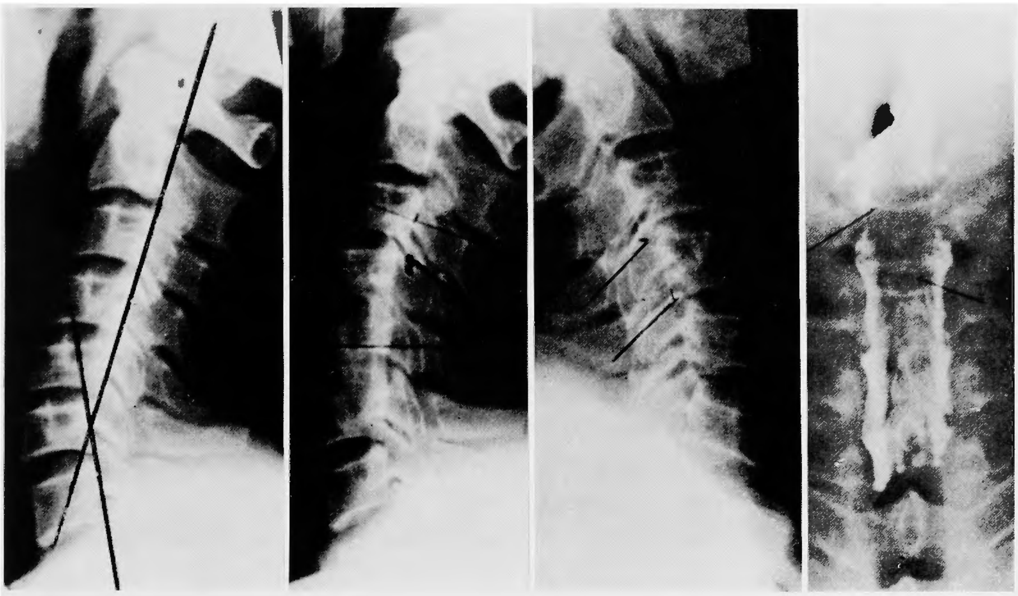


Fig. 13. a) Postoperative Instability of C3–4. b) Dynamic Canal Stenosis of C3–4 and C4–5.

Patterns of Myelographic Defects

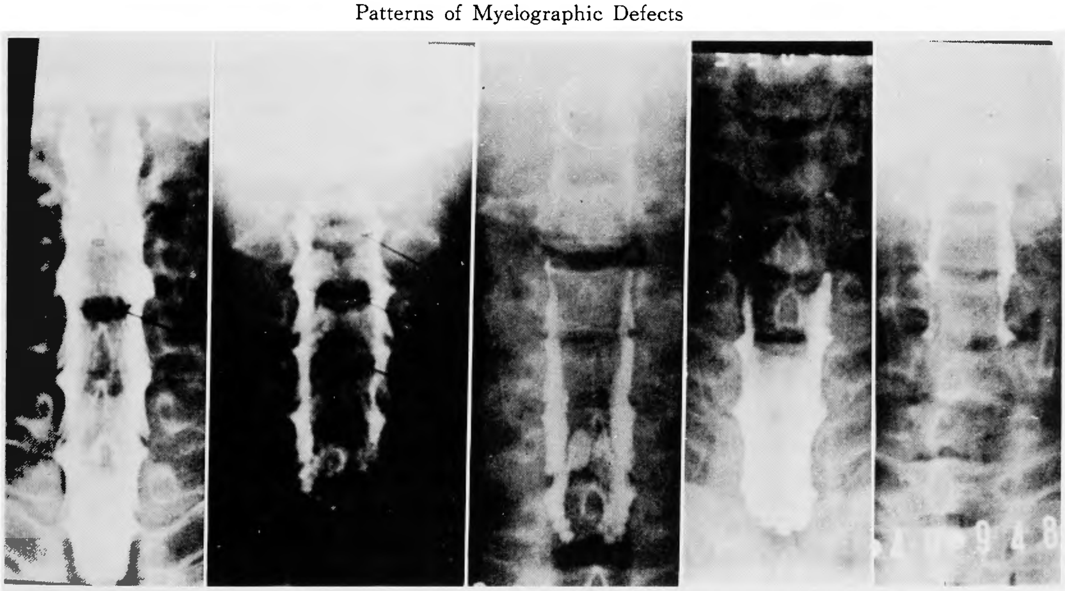


Fig. 14. Central Defect Lateral Narrowing Lateral Dropping Complete Blockage

I 2 3 4

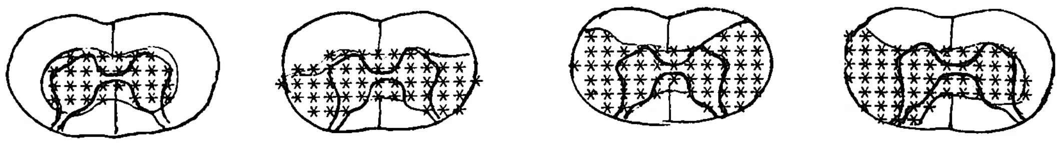


Fig. 15. Central Type
central area inner part of posterior column and pyramidal tract

Posterolateral type
1+pyramidal tract and spinocerebellar tract

Transverse Type
2+spinothalamic tract

Brown-Sèquard Type

Type	1	14 cases
	2	47
	3	65
	4	4

Type I myelopathy produced dynamically in slight compression shows neurologically the segmental signs and the pyramidal signs in the upper limbs resulting from the lesion in the central area.

Type 2 myelopathy produced in moderate compression, to add to the signs of type I, includes the pyramidal signs and the spinocerebellar signs in the lower limds resulting from the resions in the posterolateral arecs.

Type 3 produced in severe compression furthermore includes the spinothalamic signs resulting from the lesions of the anterolateral areas.

Type 4 produced in a paramedian compression shows so-called Brown-Sèquard syndrome.

Deep sensory disturbance are out of the criteria of this classification.

By analyzing neurologically, these clinical cases were classified into these types. The clinical types are diagramed and each incidence is shown in Table 7.

It was then discussed radiographically and myelographically whether the clinical patterns would have any connection with the intensity of cord compression. Consequently, it became apparent that the neurological severity of the cord lesion was almost consistent with the intensity of cord compression presumed radiologically.

It is theoretically thought that the patterns of myelopathy progress from type I to type 2 and finally to type 3. Sometimes, however, it happens that the clinical course expected according to the patient's description does not always concur with that presumed experimentally. However, it is recognized to be the reverse course against the progress of the symptoms. That is, superficial sensory disturbance due to the lesion of the anterolateral areas tend to improve early and almost completely, whereas spastic motor disturbances due to the severe lesions of the central area and the posterolateral areas tend only to improve later and incompletely, and sometimes do not

Table 10. Effect of Immobilization by Interbody Fusion - Neurological and functional improvement of the upper and lower limbs

• remarkably improved	27%	33%
• improved	31	41
• slightly improved	27	21
• unchanged	13	3.3
• deteriorated	2	0

after 1967

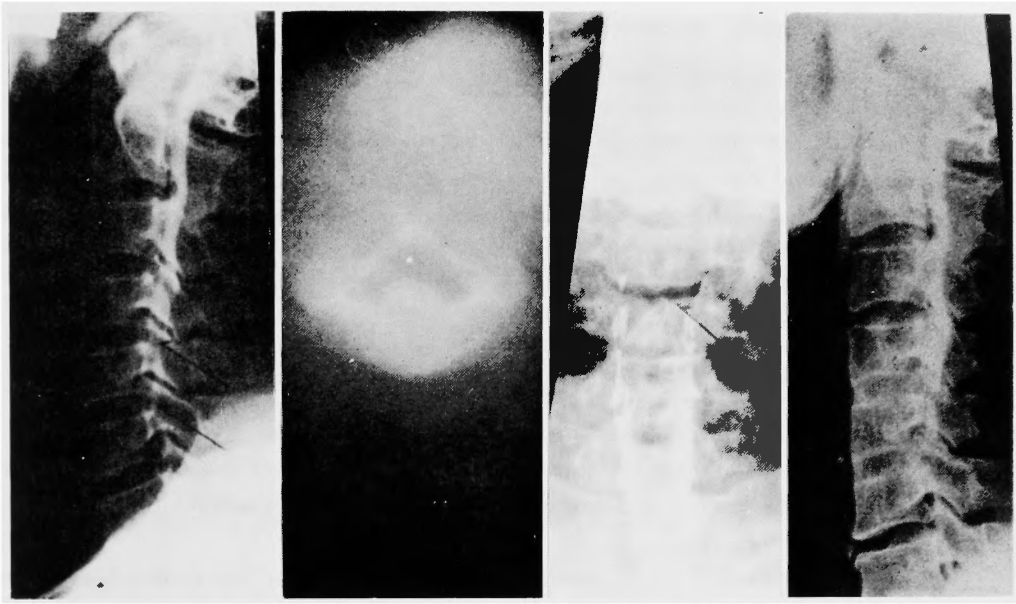


Fig. 16. Ossification of the Posterior Longitudinal Ligament in a Plain Film and a Transvers Tomogram.
The symptoms were improved remarkably after fusion of C4–5 and C5–6 with intervertebral mobility.

even improve. This indicates that the central area and the posterolateral areas are more damaged and mostly already irreversible, while the anterolateral areas are scarcely damaged and relatively reversible.

b. Effects of immodilization by anterior spinal fusion

The operative results of interbody fusion for 100 cases are shown in Table 8. The results were obtained from neurological and functional evaluations of the preoperative and the postoperative findings. This operative method without removing the posterior spur aims at gaining the intervertebral stability and changing the dynamic cord compression to the static cord compression. This indicates that the stability of the pathogenetic level may lead to the significant improvement of the symptoms. Postoperative improvement including the grade of "slightly" to "remarkably improved" was noticed in more than 96 percent.

Interbody fusion should performed even on the degenerative, suspected levels because of preventing the danger of the pathogenetic change in the near future.

This also indicates that the dynamic stresses may play a significant part of the

Table 11. My Conception of Pathogenesis

Cord Compression

primary ——local, strangulating, frictional

secondary—— intramedullary mechnical damage and vascular ischemia

Selective Cord Lesion

reversible or irreversible

Spondylotic Myelopathy

neurological symptoms and signs

Intramedullary Compressive Stresses ⟶
Intramedullary Vascullar Changes = Ischemia and Damage

pathogenesis of myelopathy in cervical spondylosis.

Conclusion

It is concluded that the selective cord lesion, neurologically reflecting cervical spondylotic myelopathy and concealing its pathogenesis may be produced basically due to the mechanical stresses, increasing by repeated movements of the cervical spine and secondarily due to the ischemia of the specific blood vessels in the cord. My hypothesis is shown in Table 11.

Summary

At first, the dynamic nature of the cervical cord in cross-section was observed and its intensity wcs measured using the bovine cord obtained immediately after slaughter.

Then, the stress distbirution in the cord in compression was maped out from the dynamical analysis due to the two-dimensional photo-elastic experiment using the cord models of polyurethane rubber.

Consequently, the stresses concentrated on the central area and the outer edges of the posterolateral ares. These areas were dynamically weaker and more fragile than the outer areas of the anterior and the posterior column compressed directly.

And also, the relationship between the pathways of the blood vessels and the stresses in the cord were discussed. It was presumed that the selective cord lesion seen in this condition would be produced by the stresses and the subsequent ischemia in the cord.

Furthermore, it was discussed radiologically and neurologically whether the hypothesis presumed experimentally could be accepted clinically.

In conclusion, it is suggested that the pathogenesis of cervical spondylotic myelopathy has a basical and significant relationship to interaction between the mechanical stresses and the subsequent ischemia in the cord which are set up dynamically by compression, reinforcing by the movements of the cervical spine with the narrowed canal.

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和文抄録

頸椎症性脊髄症の成因

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本症において，脊髄の椎管前方の骨軟骨性突出および後方の黄靱帯・椎弓により，前後方向からの圧迫に対し脊髄横断面傷害域は直接の圧迫を受ける前索および後索の外側にはみられず，直接の圧迫を受けない脊髄中心部および側索部に特異的，選択的にみられる．

この脊髄傷害域の成立が，単に機械的圧迫のみでは説明できないとして，今日まで，数多くの血行障害が唱えられてきた．しかし，いまだ mysterious のままである．本研究は，脊髄内の機械的圧迫の影響をとらえるべく，新鮮牛頸髄への圧迫・破壊実験，灰白質・白質の力学的強度の測定，光弾性頸髄模型による脊髄内応力分布の解析，静的圧迫と繰り返しの動的圧迫実験，脊髄中心部と側索部の力学的抵抗減弱域と髄内血行分布との関係などを調べることにより，本症発症の基盤となる脊髄傷害域が髄内応力による機械的傷害と，それに引続く，二次的な髄内血行障害により成立することを提唱せしめた．

この実験結果を臨床的にも解明すべく，臨床症例の神経学的，レ線学的分析を行ない，神経症状の程度と圧迫度との相関々係を調べた．

結論として，狭小化された椎管内の頸髄は，頸椎運動に伴って機械的圧迫を強く受ける．機械的傷害と二次的髄内血行傷害により組織傷害域は拡大し，髄内に特異的，選択的傷害域の成立をみるにいたる．これを反映して，本症にみる多彩であるも特徴的なる脊髄症状を呈するにいたると考えられる．